

Search for octupole correlations in ^{147}Nd

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Properties of excited states in ^{147}Nd have been studied with multispectra and $\gamma\gamma$ coincidence measurements. Twenty-four new γ -lines and three new levels have been introduced into the level scheme of ^{147}Nd . Lifetimes of eight excited levels in ^{147}Nd , populated in the β decay of ^{147}Pr , have been measured using the advanced time-delayed $\beta\gamma\gamma(t)$ method. Reduced transition probabilities have been determined for 30 γ -transitions in ^{147}Nd . Potential energy surfaces on the (β_2, β_3) plane calculated for ^{147}Nd using the Strutinsky method predict two single quasiparticle configurations with nonzero octupole deformation, with $K=1/2$ and $K=5/2$. We do not observe parity doublet bands with $K=5/2$. For pair of opposite parity bands that could form the $K=1/2$ parity doublet we were able only to determine lower limit of the dipole moment, $|D_0| \geq 0.02 \text{ e}\cdot\text{fm}$.

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I. INTRODUCTION

Lowered excitation energies of the first 1^- states, fast E1 transitions between the $K^\pi = 0^-$ and ground state bands and high $|D_0|$ values observed in the even-even $^{146-150}\text{Nd}$ isotopes constitute an evidence that these nuclei belong to the octupole deformation region in lanthanides. Also theory assigns these isotopes to the octupole region [1, 2]. This same one should expect for the odd-N neodymium isotopes from this mass region. In these isotopes one should observe parity doublet bands connected by strong E1 transitions with high $|D_0|$ moments. However in Ref. [3] in which the properties of ^{149}Nd isotope have been studied we have obtained very low $|D_0|$ values for the lowest pair of opposite parity states which should constitute parity doublet in this isotope. In the present work we have undertaken investigations of octupole correlations in ^{147}Nd .

Excited states in ^{147}Nd have been previously studied in the β -decay of ^{147}Pr [4–6], in the neutron capture reaction [7, 8] and in the transfer reactions [9–12]. Recently, high-spin states in ^{147}Nd have been studied with the use of the heavy ion induced fusion-fission reaction [13]. Multipolarities of several γ -transitions in ^{147}Nd have been established in Refs. [6, 8] by internal-conversion electron measurements. Lifetimes of the lowest levels in ^{147}Nd have been measured in Refs. [6, 10]. Experimental data concerning the ^{147}Nd nucleus are gathered in a recent compilation [14]. Despite of a rather big body of experimental data on ^{147}Nd no firm configuration assignment for excited levels was proposed and there is no experimental information on octupole correlations in ^{147}Nd . In order to obtain a better understanding of the low energy structure and to get information on octupole strength in of ^{147}Nd we have measured lifetimes of the excited

states in this nucleus using the advanced time-delayed $\beta\gamma\gamma(t)$ method [15–17]. The experimental methods are briefly described in Section II, while a new level scheme for ^{147}Nd and the lifetime results are presented in Section III of this paper. In Section IV experimental results are discussed and results of theoretical calculations are presented. In particular, results of potential energy calculations on the (β_2, β_3) plane and theoretical values of $|D_0|$ moments are shown.

II. EXPERIMENTAL DETAILS

Measurements were carried out at the OSIRIS on-line fission-product mass separator at Studsvik in Sweden [18]. Excited states in ^{147}Nd were populated in the β -decay of ^{147}Pr , which was obtained via a chain of β -decays starting from the ^{147}Cs and ^{147}Ba isotopes,

$$^{147}\text{Cs} \xrightarrow{0.230\text{s}} ^{147}\text{Ba} \xrightarrow{0.894\text{s}} ^{147}\text{La} \xrightarrow{4.06\text{s}} ^{147}\text{Ce} \xrightarrow{56.4\text{s}} \\ \rightarrow ^{147}\text{Pr} \xrightarrow{13.4\text{min}} ^{147}\text{Nd}.$$

The $A=147$ nuclei were produced in the fission reaction of ^{235}U induced by the thermal neutrons from the R2-0 reactor at Studsvik. The ^{235}U target consisted of about 1 g of uranium dispersed in graphite. The $A=147$ activity, mass separated from other fission products, was deposited onto an aluminized Mylar foil in a moving-tape collection system at the center of the experimental setup. Each measuring cycle was divided into eight sequential time-bins, each lasting 40 s. To 'clean up' spectra from the activities coming from the ^{147}Pr predecessors our radioactive samples were cumulated during first 135 s of each cycle. Then the beam was deflected and the data were collected during the rest of the cycle.

Two experiments have been performed. In the first one the multispectra (MSS) and β -gated $\gamma\gamma$ coincidence data have been collected. In this experiment one LEP Ge detector with energy resolution FWHM of 0.6 keV at

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81 keV, one 30% HPGe detector with FWHM of 2.1 keV and one 80% HPGe detector with FWHM of 2.9 keV at 1333 keV have been used. A 3 mm thick NE111A plastic scintillator was used as a β -detector. About 1.2×10^8 double coincident events have been collected.

In the second experiment lifetime measurements have been performed using the advanced time-delayed $\beta\gamma\gamma(t)$ method [15–17]. In this method the fast timing information was derived from coincidences between fast-response β - and BaF_2 γ -detectors, while an additional coincidence with a Ge γ -detector was used to select the desired γ -cascade. In this experiment the setup consisted of one BaF_2 detector, one HPGe detector with efficiency of 30% and FWHM of 2.1 keV at 1333 keV, and one β -detector. The latter was a 3 mm thick ΔE NE111A plastic detector to ensure almost constant, independent of the β -particle energy, time response of the fast timing system. About 2.2×10^6 β -Ge- $\text{BaF}_2(t)$ coincident events have been collected. Several sets of the β -gated coincidence γ -ray spectra from the Ge and BaF_2 detectors and triple coincidence $\beta\gamma\gamma(t)$ time-delayed spectra have been sorted in the off-line analysis. Gating conditions set on the β -spectrum were chosen to keep the time response constant in the whole range of selected β particle energies.

III. EXPERIMENTAL RESULTS

The results for ^{147}Nd are presented in Figs. 1 – 4 and in Tables I and II. Gamma-lines were assigned to the ^{147}Nd level scheme based on the MSS and $\gamma\gamma$ coincidence results. Fig. 1 presents examples of the decay curves for γ -transitions emitted in the β -decay of ^{147}Pr obtained in the MSS measurements. The average half-life of ^{147}Pr obtained from these measurements, 13.39(4) min, is in agreement with value 13.4(3) min given in Ref. [14].

The level scheme was constructed based on the β -Ge-Ge data. Moreover several lines were placed in the level scheme based on the energy fit. Examples of coincident γ -ray spectra collected with the Ge detectors are shown in the upper panels of Figs. 2 – 3, while a new level scheme for ^{147}Nd is presented in Fig. 4. Level and gamma-ray energies and gamma-ray intensities determined in the present work are given Tables I and II. Where available, the E2/M1 mixing ratios of γ -transitions were taken from Ref. [14].

In general our level scheme for ^{147}Nd agrees well with the one obtained by Shibata *et al.* [6]. Twenty-four new γ -lines and three new levels have been introduced into the decay scheme of ^{147}Pr . They are marked with asterisks in Figs. 4a–c and in Tables I and II. New levels have energies 830.0, 1761.9 and 2070.4 keV. The latter two may correspond to the 1759 ± 5 and 2068 ± 5 keV levels, observed in the transfer reactions [14]. Also the ^{147}Pr β -decay data obtained with the total absorption γ -ray spectrometer [19] indicate existence of states with similar excitation energies in ^{147}Nd . For completeness weak transitions, which have not been observed in our

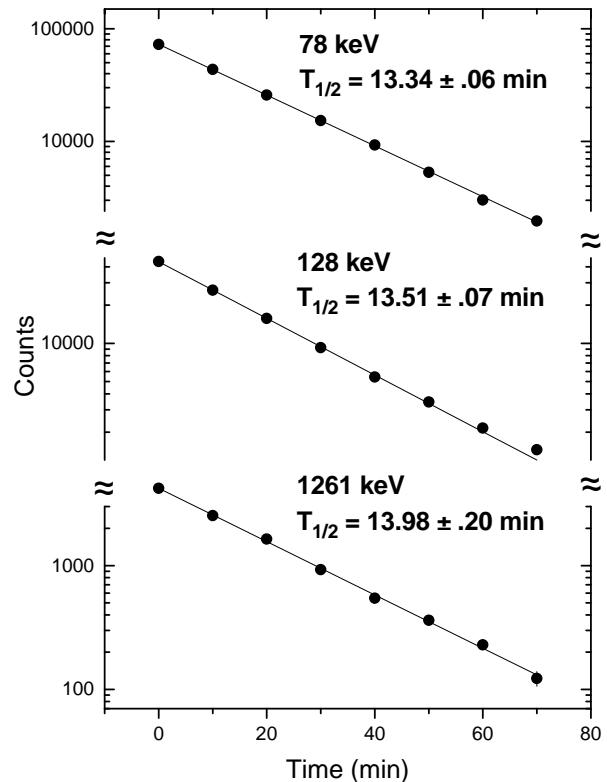


FIG. 1: Examples of the decay curves of γ rays from the β decay of ^{147}Pr obtained in the MSS measurements.

spectra due to limited statistics but which have been reported in Ref. [14], are drawn with dotted lines in the level scheme.

Level lifetimes were determined from the analysis of the triple coincidence β -Ge- BaF_2 data. Examples of γ -ray BaF_2 spectra coincident to the gating transitions selected in the Ge detector are shown in the lower panels of Figs. 2 – 3.

Lifetimes longer than about 40 ps, which manifest themselves by a strong asymmetry (or slope) on the delayed side of the time spectra, have been determined using the de-convolution method [15]. Examples of such time-delayed spectra for the 127.9, 214.6 and 314.7 keV levels in ^{147}Nd are shown in Fig. 5. The fitted function includes four free parameters, namely position and Full-Width-at-Half-Maximum of Gaussian, which approximates prompt time response of the timing detectors, the half-life value and one parameter, which provides an overall re-normalization between the experimental and fitted time spectra. More details on the fitting procedures are given in Ref. [15]. The half-lives for the levels at 49.9, 127.9, 214.6, 314.7 and 604.5 keV have been determined

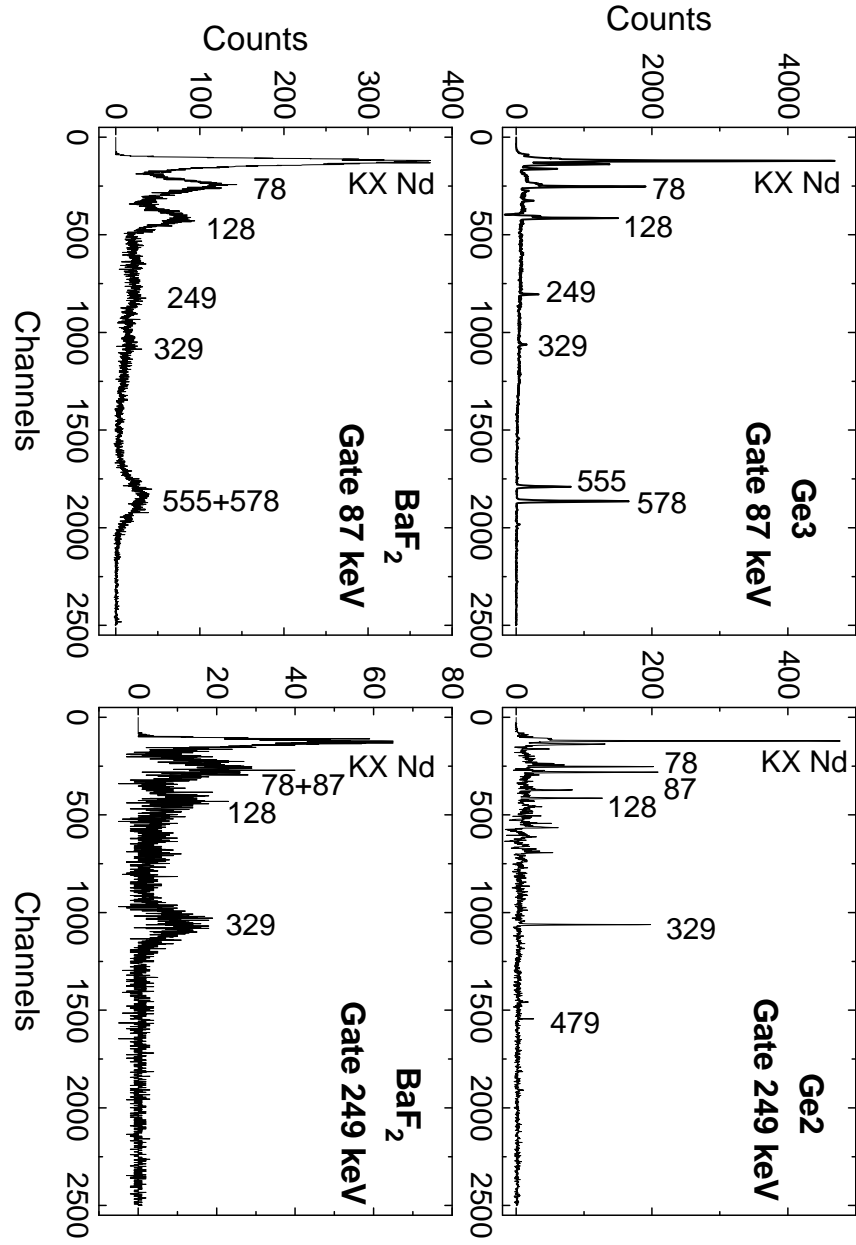


FIG. 2: Coincident γ -ray spectra from the Ge and BaF₂ detectors. Left top panel shows spectrum from the 80% HPGe detector gated by the 86.7 keV line in the LEP detector. Right top panel shows spectrum from the 30% HPGe detector gated by the 249.0 keV line in the LEP detector. Panels at the bottom show the corresponding coincident spectra sorted onto the BaF₂ detector from the β -Ge-BaF₂ data.

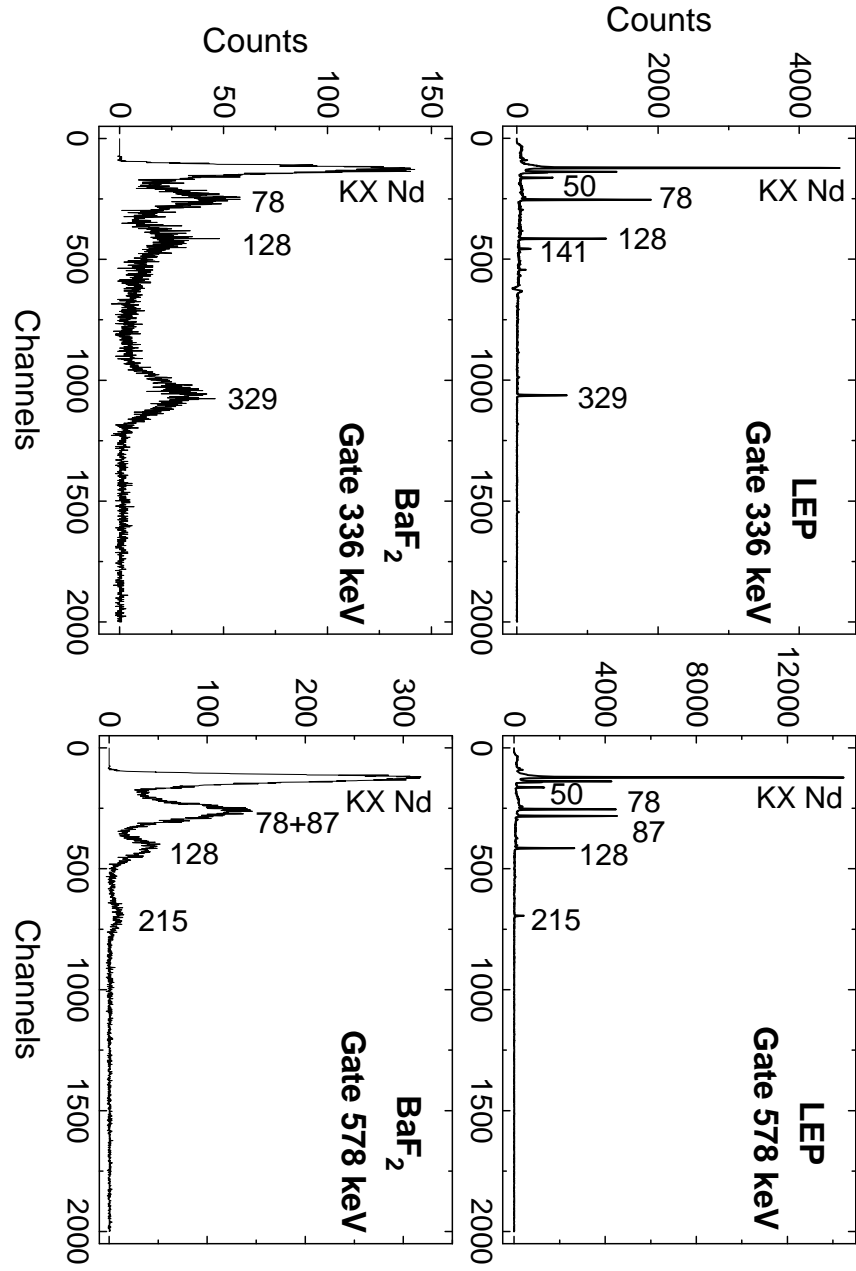


FIG. 3: Coincident γ -ray spectra from the Ge and BaF₂ detectors. Left top panel shows spectrum from the LEP detector gated by the 335.7 keV line in the 30% HPGe detector. Right top panel shows spectrum from the LEP detector gated by the 578.0 keV line in the 80% HPGe detector. Panels at the bottom show the corresponding coincident spectra from the BaF₂ detector.

TABLE I: Level lifetimes and experimental reduced transition probabilities in ^{147}Nd observed in the β -decay of ^{147}Pr . New γ transitions are marked with asterisk.

Initial level [keV]	$I_i^\pi K_i$	$T_{1/2}$ this work [ps]	$T_{1/2}$ ref. [14] [ns]	E_γ [keV]	I_γ	$I_f^\pi K_f$	$M\lambda^a$	α_{TOT}^b	$B_{exp}(M\lambda)^c$
49.9	$7/2^- 5/2$	808(111)	1.0(3)	49.921(4)	48(5)	$5/2^- 5/2$	M1	10.5	$>2.3 \cdot 10^{-2}$
							E2	31.3	$<2.3 \cdot 10^4$
127.9	$5/2^- 1/2$	390(23)	0.4(1)	78.003(5)	122(12)	$7/2^- 5/2$	M1	2.85	$>3.0 \cdot 10^{-2}$
							E2	5.4	$<1.6 \cdot 10^4$
				127.941(6)	100(10)	$5/2^- 5/2$	M1	0.71	$>5.9 \cdot 10^{-3}$
							(E2)	0.91	$<8.3 \cdot 10^2$
214.6	$1/2^- 1/2$	4.59(22) ns	4.53(6)	86.698(5)	69(7)	$5/2^- 1/2$	E2	3.9	$4.8(5) \cdot 10^3$
				214.601(6)	19(2)	$5/2^- 5/2$	E2	0.155	$1.4(2) \cdot 10^1$
314.7	$3/2^- 3/2$	54(7)	≤ 0.1	100.090(8)	5.5(5)	$1/2^- 1/2$	(M1)	1.5	$1.3(2) \cdot 10^{-2}$
				186.764(6)	11.7(12)	$5/2^- 1/2$	M1	0.25	$4.4(7) \cdot 10^{-3}$
				264.74(4)	4.0(4)	$7/2^- 5/2$	E2	.082	$1.1(2) \cdot 10^2$
				314.728(6)	255(25)	$5/2^- 5/2$	M1	0.06	$7.4(-41_{+38}) \cdot 10^{-3}$
							E2	0.047	$1.8(+7_{-6}) \cdot 10^3$
463.6	$3/2^- 1/2$	26(4)	≤ 0.1	149.0(1)	0.4(1)	$3/2^- 3/2$	M1	0.46	$1.8(5) \cdot 10^{-3}$
				249.044(8)	15.3(15)	$1/2^- 1/2$	M1	0.112	$8.8(-82_{+57}) \cdot 10^{-3}$
							E2	0.095	$1.3(+19_{-13}) \cdot 10^3$
				335.719(6)	67(7)	$5/2^- 1/2$	E2	0.039	$3.1(6) \cdot 10^3$
							(M1)	0.052	$1.9(11) \cdot 10^{-3}$
				413.675(9)	13.3(13)	$7/2^- 5/2$	E2	0.0208	$2.3(4) \cdot 10^2$
				463.53(5)	2.8(3)	$5/2^- 5/2$	M1	0.022	$4.1(8) \cdot 10^{-4}$
604.5	$1/2^- 1/2$	76(38)	<0.8	86.69(5)*	1.6(2)*	$5/2^- 3/2$	(E2)	3.85	$1.0(5) \cdot 10^5$
				140.904(8)	3.3(3)	$3/2^- 1/2$	(M1)	0.54	$2.5(13) \cdot 10^{-2}$
				389.94(6) ^d	0.6(2) ^d	$1/2^- 1/2$	(M1)	0.0345	$2.2(13) \cdot 10^{-4}$
				476.80(6)*	1.6(2)*	$5/2^- 1/2$	(E2)	0.0138	$2.0(10) \cdot 10^1$
				604.54(5)	9.1(9)	$5/2^- 5/2$	(E2)	0.0075	$3.5(18) \cdot 10^1$
769.4	$3/2^+ 1/2$	≤ 16		305.70(4)	2.4(2)	$3/2^- 1/2$	(E1)	0.0135	$\geq 7.5 \cdot 10^{-6}$
				454.64(5)	1.4(1)	$3/2^- 3/2$	(E1)	0.005	$\geq 1.3 \cdot 10^{-6}$
				554.769(8)	76(8)	$1/2^- 1/2$	E1	0.00315	$\geq 4.0 \cdot 10^{-5}$
				641.392(8)	215(22)	$5/2^- 1/2$	E1	0.0023	$\geq 7.3 \cdot 10^{-5}$
				719.49(7)	3.8(4)	$7/2^- 5/2$	(M2)	0.0205	$\geq 2.1 \cdot 10^2$
				769.32(8)	4.8 (5)	$5/2^- 5/2$	(E1)	0.00155	$\geq 9.4 \cdot 10^{-7}$
792.6	$3/2^+$	≤ 16		160.99(4)	1.7(2)	$3/2^-$	(E1)	0.072	$\geq 3.6 \cdot 10^{-5}$
				328.894(6)	55(6)	$3/2^- 1/2$	E)	0.011	$\geq 1.4 \cdot 10^{-4}$
				477.841(8)	56(7)	$3/2^- 3/2$	E1	0.00435	$\geq 4.6 \cdot 10^{-5}$
				577.973(8)	187(19)	$1/2^- 1/2$	E1	0.00285	$\geq 8.7 \cdot 10^{-5}$
				664.60(7)	3.1(3)	$5/2^- 1/2$	(E1)	0.0215	$\geq 9.5 \cdot 10^{-7}$

^a γ -ray multipolarities and $\delta^2(\text{E2/M1})$ mixing ratios are taken from Ref. [14].

^bTotal internal conversion coefficients are taken from ref. [20].

^cIn units $\text{e}^2 fm^2$ for E1 transitions, $\text{e}^2 fm^4$ for E2 transitions, μ_N^2 for M1 transitions and $\mu_N^2 fm^2$ for M2 transitions.

^d γ -ray energy is from Ref. [14]. γ -ray intensity is re-calibrated from data of Ref. [14].

by the de-convolution method.

Lifetimes shorter than 40 ps were measured using the centroid shift method [15], in which the mean lifetime $\tau = T_{1/2}/\ln 2$ is determined as a shift of the centroid of the time-delayed spectrum from the prompt curve at a given γ -ray energy. This method is based on the concept

of a two γ -ray cascade [15]. When a gate on the Ge detector is set on the bottom member of the γ -ray cascade, de-exciting intermediate state, and a gate on the BaF₂ detector is set on the top γ -ray, de-exciting high energy excited state in a nucleus, one obtains first centroid position of the time-delayed β -BaF₂ spectrum giving a ref-

TABLE II: Energies and intensities of γ -lines in ^{147}Nd not listed in Table I. New γ transitions and new levels are marked with asterisks.

E_γ [keV]	I_γ	Initial level [keV]	E_γ [keV]	I_γ	Initial level [keV]
165.02(4)*	1.5(2)*	957.4	1036.38(8)	1.9(2)	1350.9
167.88(4)	2.1(2)	631.5	1046.06(8)*	1.8(2)*	1261.0
202.03(4)	1.6(2)	516.7	1080.4(1)*	1.1(1)*	1544.6
239.1(1)*	0.6(1)*	1350.9	1083.59(7)	10.6(10)	1398.2
310.7(1)*	0.7(1)*	942.2	1096.03(8)	3.2(3)	1310.7
316.89(5)	1.2(1)	631.5	1099.92(9)	2.9(3)	1616.6
366.59(5)*	1.6(2)*	830.0*	1102.0(1)*	1.3(1)*	1733.7
388.816(8)	18(2)	516.7	1129.95(9)	2.5(3)	1593.5
416.9(1)	0.9(1)	631.5	1130.2(2)*	0.6(1)*	1761.9*
437.25(5)	1.6(2)	1041.7	1136.53(7)	19(2)	1350.9
466.85(3)	18(2)	516.7	1152.6(1)	2.3(2)	1616.6
468.37(5)*	1.9(2)*	1261.0	1156.8(1)	1.5(1)	1673.5
478.51(8)*	3.8(4)*	942.2	1182.77(8)	14.0(14)	1310.7
491.70(5)	4.8(5)	1261.0	1214.3(1)	4.2(4)	1264.1
493.53(7)	1.1(1)	957.4	1217.1(1)	2.0(2)	1733.7
494.9(1)*	0.7(1)*	1264.1	1230.08(9)	2.2(2)	1544.6
503.61(5)	4.8(5)	631.5	1261.11(9)	54(5)	1261.0
516.68(3)	15(1)	516.7	1264.24(9)	15.3(15)	1264.1
518.43(8)*	1.0(1)*	1310.7	1298.5(1)*	1.3(2)*	1761.9*
596.1(2)	0.6(1)	1112.3	1300.54(9)	29(3)	1350.9
615.07(6)*	4.8(5)*	830.0*	1302.0(1)	2.9(3)	1616.6
627.52(8)	4.4(4)	942.2	1310.64(9)	7.1(7)	1310.7
631.54(5)	9.7(10)	631.5	1358.9(1)	2.6(3)	1673.5
642.42(8)	1.2(1)	957.4	1398.4(2)	1.4(3)	1398.2
656.46(7)	2.3(2)	1261.0	1416.9(1)	2.7(3)	1544.6
706.12(7)	6.9(7)	1310.7	1465.2 (1)	1.6(2)	1593.5
718.97(7)	4.7(5)	1350.9	1518.0(2)*	1.6 (2)*	2310.2
726.6(1)	0.6(1)	1041.7	1543.6(1)	3.0(3)	1593.5
746.45(7)	3.6(4)	1350.9	1547.2(1)*	2.3(2)*	1761.9*
746.9(1)*	1.3(1)*	1264.1	1560.4(2)	0.8(2)	2164.7
793.93(5)	17.8(1.8)	1310.7	1593.7(1)	2.5(3)	1593.5
797.23(8)	2.0(2)	1112.3	1605.9(1)	1.1(1)	1733.7
800.49(8)	2.3(2)	1264.1	1616.6(2)*	0.9(2)*	1616.6
814.2(1)	1.3(1)	942.2	1623.5(1)	3.4(3)	1673.5
840.4(1)	1.1(1)	1444.8	1673.8(2)	1.8(2)	1673.5
847.02(8)	3.0(3)	1310.7	1683.7(2)	1.6(3)	1733.7
854.2(2)	1.4(3)	2164.1	1733.2(2)	2.3(3)	1733.7
881.51(8)	4.6(5)	1398.2	1755.6(2)*	0.5(1)*	2070.4*
887.02(8)	6.5(6)	1350.9	1793.1(2)	2.7(3)	2310.2
934.45(9)*	1.2(1)*	1398.2	1846.4(3)	0.6(1)	2310.2
942.27(8)	12.3(1.2)	942.2	1942.5(2)*	1.2(1)*	2070.4*
949.40(9)	2.1(2)	1264.1	1995.4(2)	1.6(2)	2310.2
957.8(2)	1.3(1)	957.4	2163.7(3)	1.4(3)	2164.7
981.0(1)*	1.1(1)*	1444.8	2310.3(4)	0.9(2)	2310.2
996.01(6)	20(2)	1310.7			

erence point at the energy of the top γ -ray. By reversing gates on the BaF_2 and Ge detectors, namely by selecting the top member of the cascade in the Ge detector, and the bottom member in the BaF_2 crystal we determine second time centroid position at the energy of the bottom γ -ray.

By shifting both centroids to place the first centroid on the reference time curve we obtain the meanlife of the intermediate level as a distance of the second centroid from the reference curve. The reference time curve was constructed from the β -gated $\gamma\gamma$ data measured for the

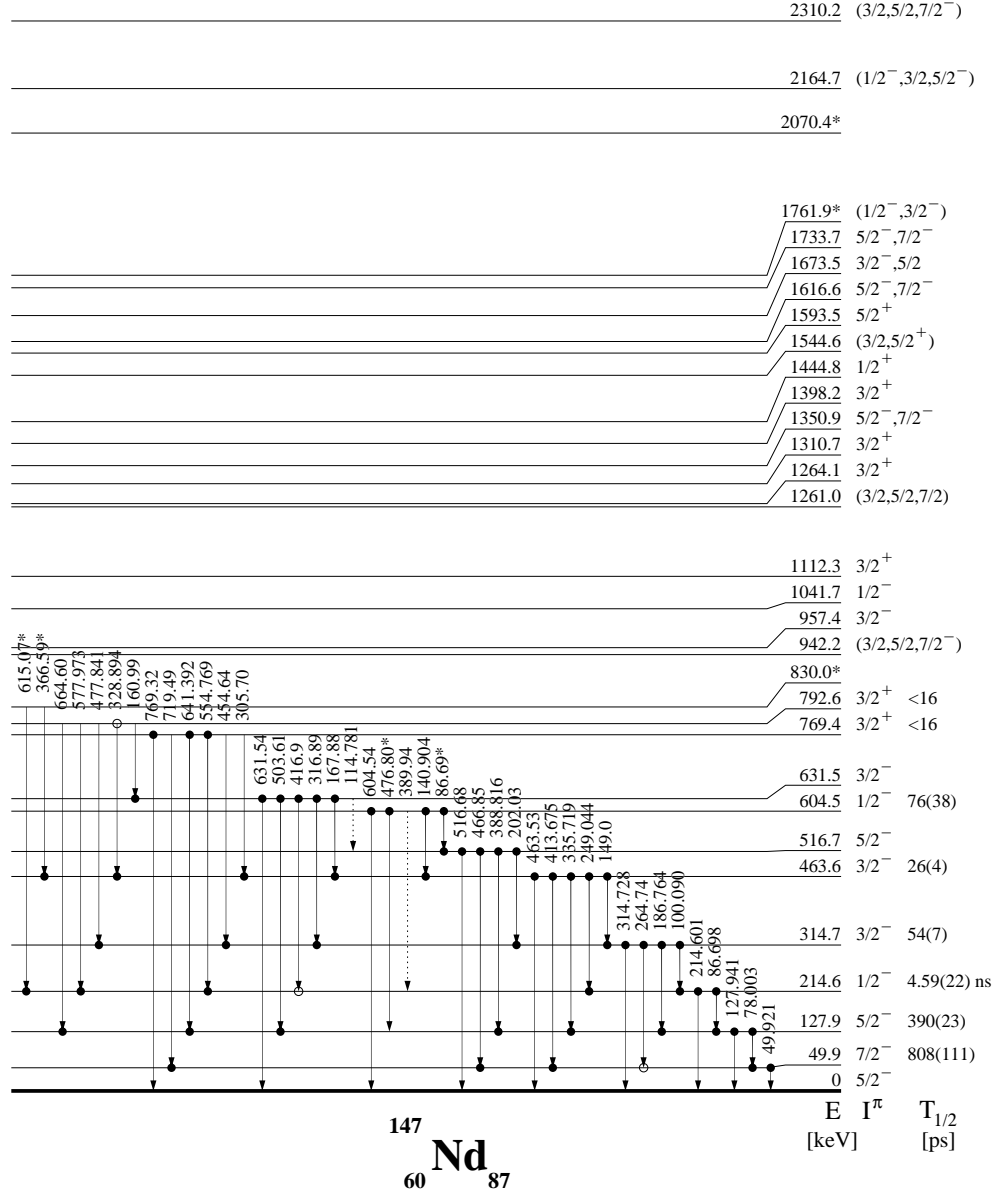


FIG. 4: The level scheme of ^{147}Nd from the β decay of ^{147}Pr . Full and empty circles indicate strong and weak $\gamma\gamma$ coincidence relations, respectively. Dotted lines mark transitions reported in Ref. [14] but not observed in our data due to limited statistics. Asterisks indicate new levels and transitions observed in this work in the β decay of ^{147}Pr .

^{138}Cs calibration source in the same experimental conditions as our data. This way a half-life of 26(4) ps was obtained for the 463.6 keV level as an average from the time spectra obtained with the 328.9-249.0, 328.9-335.7,

328.9-413.7 and 887.0-335.7 keV Ge-BaF₂ gate combinations. Examples of short half-life determination using reference curve are given in Fig. 6. Besides we have obtained half-life limits for the 769.4 and 792.6 keV levels

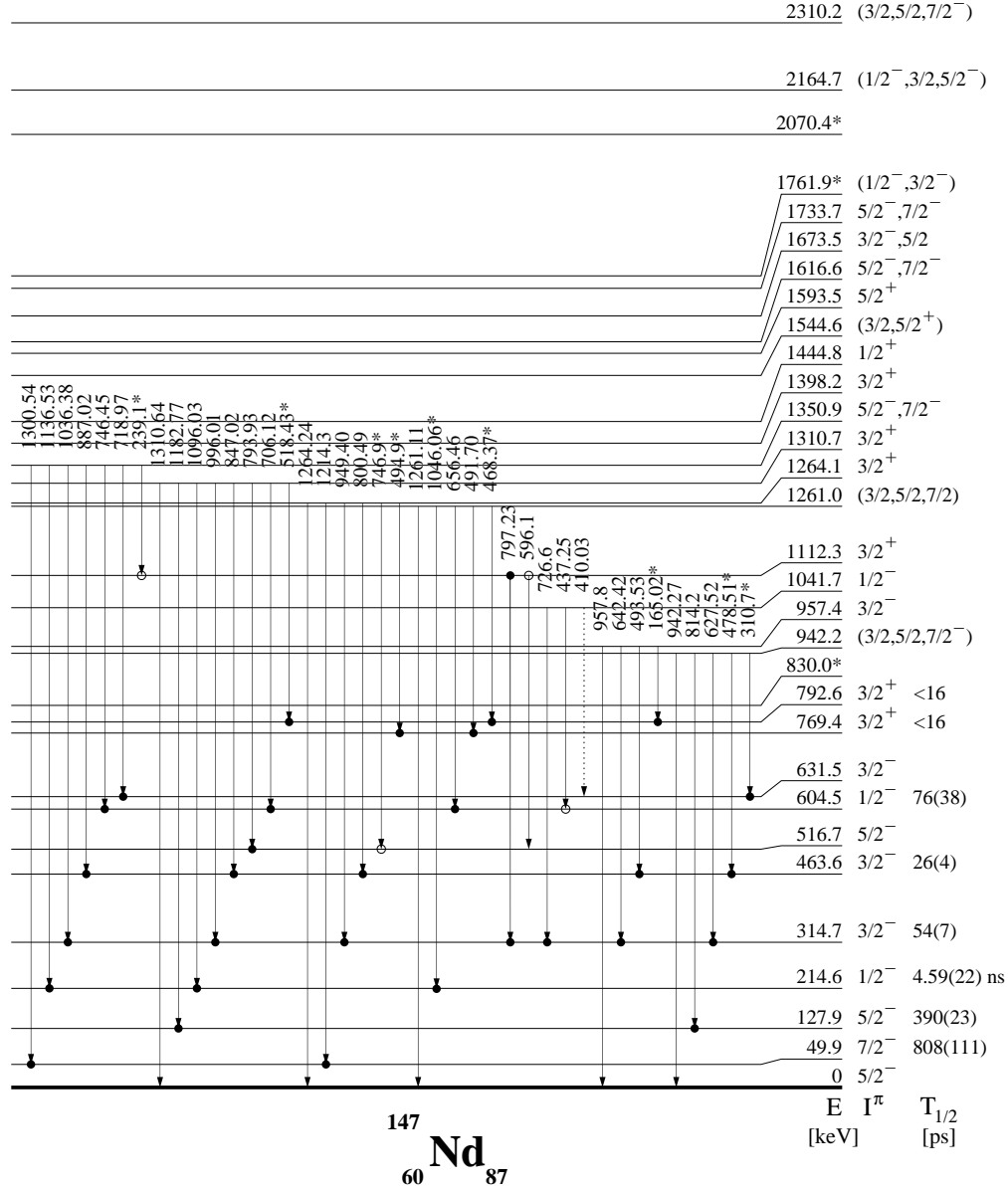


Fig. 4: (Continued).

in ^{147}Nd .

The half-life values obtained in present work for excited states in ^{147}Nd are given on the level scheme and are listed in the third column in Table I. Up to now only half-lives for first three excited states had been determined in ^{147}Nd [14]. Our half-lives obtained for these levels agree very well with values given in Ref. [14]. For next

3 excited states only the nanosecond half-life limits had been previously known (see column 4 of Table I). We have determined much more precise half-life values for them.

Reduced transition probabilities have been determined from the level lifetimes and the relative γ -ray intensities using total internal conversion coefficients from ref. [20]. Values of reduced transition probabilities obtained in this

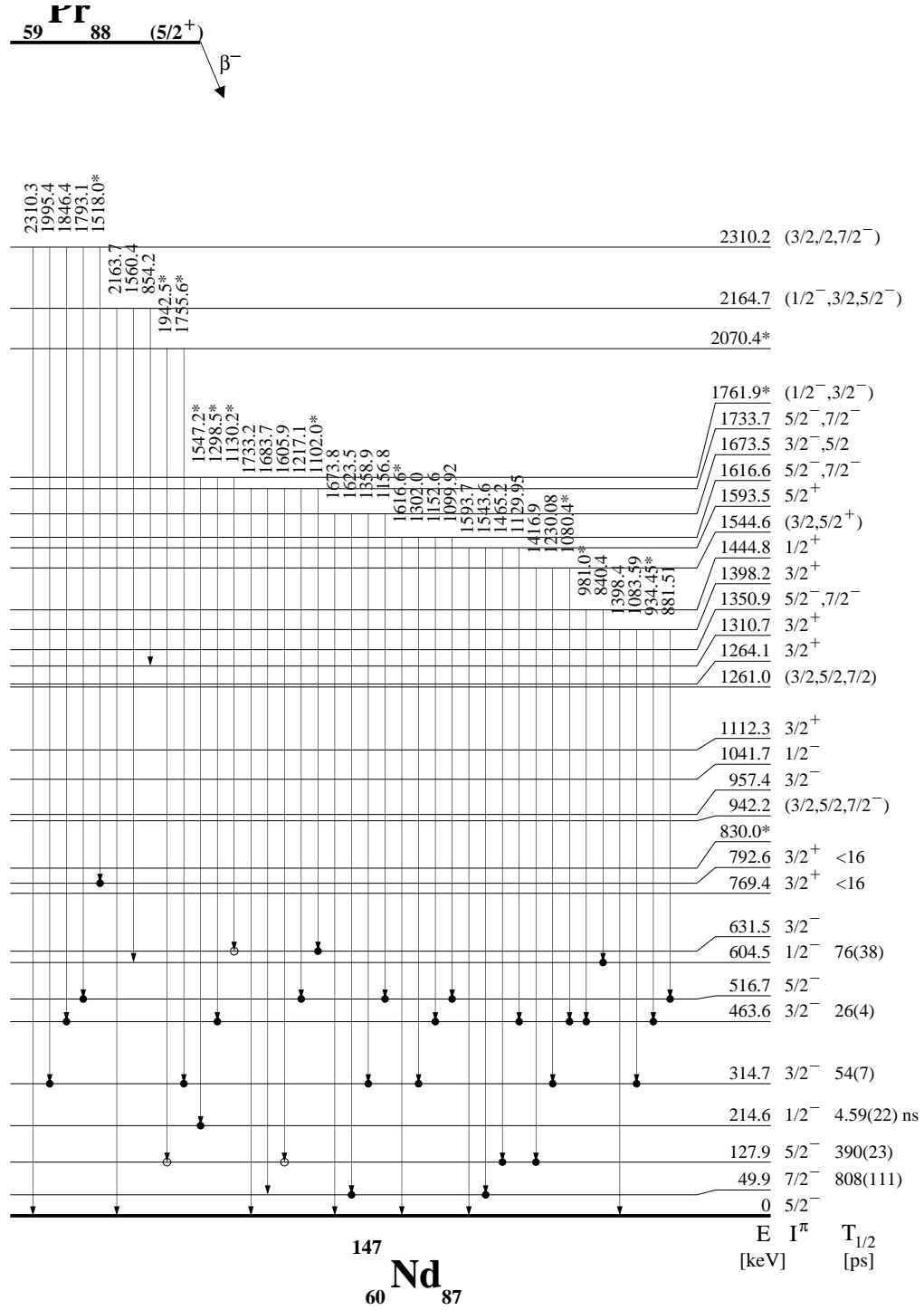


Fig. 4: (Continued).

work for 30 transitions in ^{147}Nd are listed in the last column of Table I.

IV. DISCUSSION

A. Band structure in ^{147}Nd

The occurrence of strong octupole correlations in odd-A nuclei is manifested by the presence of parity doublet bands connected by the enhanced E1 transitions with

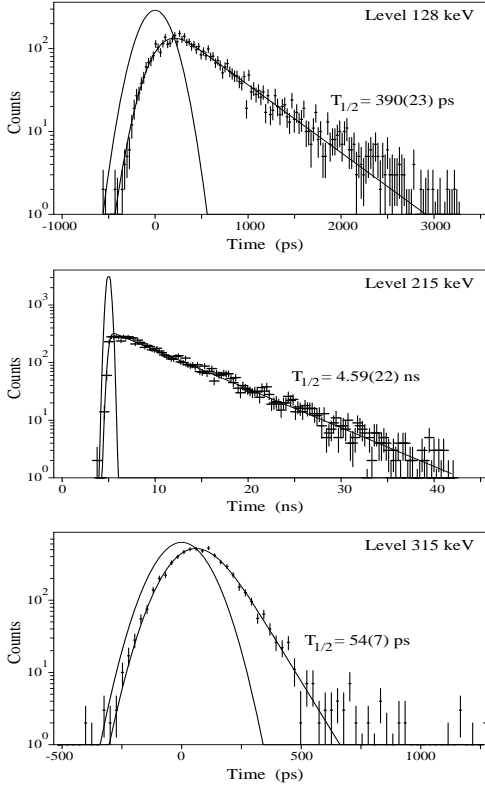


FIG. 5: Time-delayed $\beta\gamma(t)$ spectra showing slopes due to the lifetimes of the 127.9, 214.6 and 314.7 keV levels in ^{147}Nd . Each figure shows experimental points, prompt Gaussian spectrum and slope curve, which was fitted in the deconvolution process.

the reduced transition probabilities $B(E1)$ of order $10^{-3} e^2 fm^2$ [2]. In the case of parity doublet bands with $K^\pi=1/2^\pm$ the decoupling parameters are expected to be of equal magnitudes and of opposite signs.

Our potential energy calculations from Sec. IV C performed for ^{147}Nd predict two octupole-soft states with $K=1/2$ and $K=3/2$ and two octupole-deformed states with $K=1/2$ and $K=5/2$ at lowest excitation energies. So we should expect in our data two parity doublet bands, one with $K^\pi=1/2^\pm$ and one with $K^\pi=5/2^\pm$.

Ground state and the 49.9 keV state with spin $7/2^-$ are candidates for the $K^\pi=5/2^-$ band per analogy with ^{149}Nd [3]. Magnetic $|g_K - g_R|$ factor for this band deduced from the $B(M1)$ value for 49.9 keV transition treated as pure M1 would be 0.33(2), compared to 0.40(2), obtained in ^{149}Nd .

The $B(E1)$ branching ratios for 554.8 and 305.7, 641.4 and 305.7 and 641.4 and 544.8 keV transitions de-exciting the 769.4 keV level to the 214.6, 463.6 and 127.9 keV

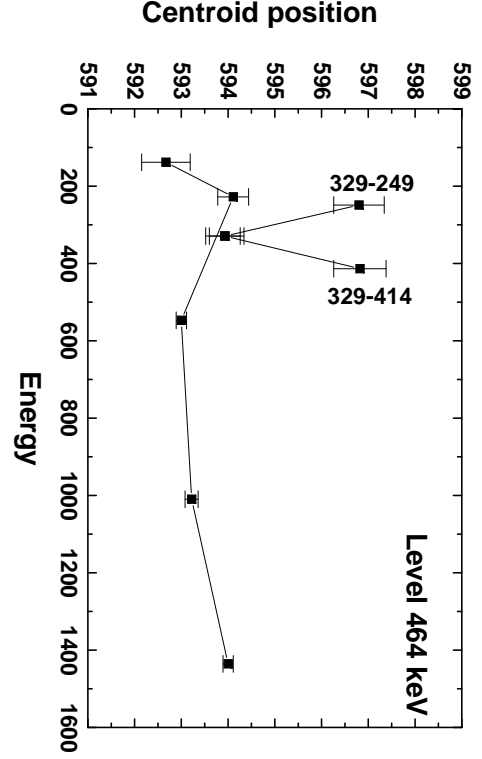


FIG. 6: Determination of the half-life for the 463.6 keV level in ^{147}Nd by centroid shift technique. The reference time curve made for ^{138}Cs calibration source is shown together with the centroid positions of time-delayed spectra marked by the energies (in keV) of γ -ray gates in the Ge and BaF_2 detectors which were used to generate them. The shift of the time-delayed centroid from the reference curve gives the mean-life of the level (calibration 12.85 ps/ch); see text for details.

states are equal 5.3(7), 9.7(13) and 1.8(3), respectively. They agree very well with the theoretical branching ratios 5.0, 9.0 and 1.8, calculated with Alaga rule [21] assuming $K=1/2$ for all four states. We suggest that 214.6, 463.6 and 127.9 keV states form the $K^\pi=1/2^-$ band in ^{147}Nd with E_0 parameter, rotational parameter A and decoupling parameter a equal 285.7 keV, 7.93 keV and 9.47, respectively. The quadrupole moment Q_0 for this band, calculated from the reduced transition probability for 86.7 keV line given in Table I, is equal $284(16) e \cdot fm^2$.

The $B(M1)$ branching ratio for 186.8 and 100.1 keV transitions (see Table I) de-exciting the 314.7 keV level to the $5/2$ and $1/2$ states of $K^\pi=1/2^-$ band is equal 0.33(8). It agrees with theoretical value 0.20 obtained with $K=3/2$ taken for the 314.7 keV level. The $B(E1)$ branching ratio for 797.2 and 596.1 keV transitions de-exciting the 1112.3 keV level to the 314.7 and 516.7 keV states is equal 1.4(3). It agrees with theoretical value 1.5 if all three states have $K=3/2$. Similar situation is obtained for 1083.6 and 881.5 keV transitions de-exciting the

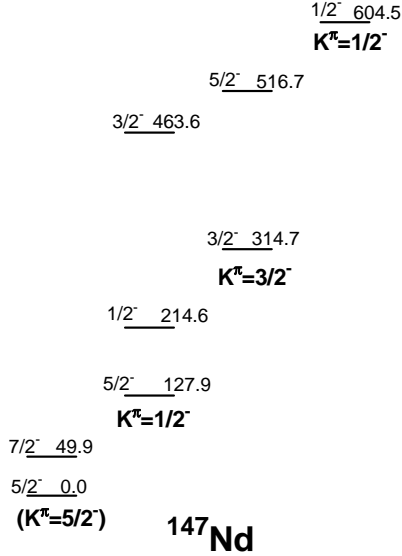


FIG. 7: Interpretation of the band structure in ^{147}Nd .

1398.2 keV level where we obtain 1.2(2) and 1.5 for experimental and theoretical values, respectively. Next B(E1) branching ratio for the 949.4 and 746.9 keV transitions de-exciting the 1264.1 keV level to the 314.7 and 516.7 keV states, equal 0.8(1), agrees with theoretical value 0.7 when the 1264.1 keV level has $K^\pi=1/2^+$ and the 314.7 and 516.7 keV states have $K^\pi=3/2^-$. Above branching ratios indicate that the 314.7 and 516.7 keV states constitute a band with $K^\pi=3/2^-$. Proposed band structure for ^{147}Nd is shown in Fig. 7.

B. Octupole correlations in ^{147}Nd

We do not observe the $K^\pi=5/2^+$ band at the lowest excitation energies in ^{147}Nd , although its population should be enhanced due to the $5/2^+$ ground state spin of the mother nucleus. Neither we see the $K^\pi=1/2^+$ band close to the ^{147}Nd ground state. The lowest excited states with opposite parity that could be candidates for the parity doublet members are the $I^\pi K=3/2^+1/2$ 769.4 keV and the $I^\pi=3/2^+$ 792.6 keV levels. We were able to determine only the upper limits of their half-lives, $T_{1/2} \leq 16$ ps, for both of them. The lower limits of the B(E1) values for the γ -transitions depopulating these two levels are given in Table I.

A generally adopted way of comparison of the E1 strength over a wider range of nuclei is offered by the intrinsic electric dipole moment, $|D_0|$, which removes the spin dependence affecting the B(E1) rates. Assuming a strong-coupling limit and an axial shape of the nucleus, the electric dipole moment, $|D_0|$, is defined (for $K \neq 1/2$) via the rotational formula:

$$B(E1) = \frac{3}{4\pi} D_0^2 \langle I_i K 10 | I_f K \rangle^2. \quad (1)$$

The $|D_0|$ moment is used as a convenient parameter for the inter-comparison even for transitional nuclei.

The lower limit of $|D_0|$ obtained for transitions de-exciting the level at 769.4 keV in ^{147}Nd to the 463.6, 214.6 and 127.9 keV states from the lower $K^\pi=1/2^-$ band is $|D_0| \geq 0.02$ efm. In case of the 792.6 keV level, if this level has $K=1/2$ the lower limit for the 328.9, 578.0 and 664.6 keV transitions de-exciting this level to the lower $K^\pi=1/2^-$ band is $|D_0| \geq 0.04$ efm and if it has $K=3/2$ it is $|D_0| \geq 0.02$ efm for the 477.8 keV transition to the $K^\pi=3/2^-$ band.

Experimental information on $|D_0|$ moments in the odd-N isotopes in lanthanides is very scarce. Reported $|D_0|$ values are very low, much lower than in the even-even neighbors, or no parity doublet bands are found at low excitation energies. Low $|D_0|$ values have been determined for ^{149}Nd [3] (see also Table III) and for ^{149}Ce [22]. Moreover, no candidates for parity doublets have been found at the lowest excitation energies in the odd N barium isotopes, ^{145}Ba [23] and ^{147}Ba [24], lying at the very center of the octupole region in lanthanides. Even the ground state spins of these two isotopes can be reproduced without involving octupole correlations [23, 24]. In ^{147}Nd we were only able to determine lower limit of $|D_0|$ for the $K=1/2$ parity doublet band, however non-observation of the $K=5/2$ parity doublet band may suggest that the $|D_0|$ values in this isotope are as low as in ^{149}Nd and ^{149}Ce .

The $|D_0|$ behavior in the odd-N isotopes in lanthanides is different from smooth dependence versus neutron number N predicted by the theory (see Table III for Nd isotopes) or observed in thorium isotopes in the actinide octupole region (see Fig. 10 in Ref. [3]). Low $|D_0|$ values in the odd-N isotopes do not result from quenching caused by opposite signs of macroscopic and shell-correction components of the dipole moment (see Sec. IV D).

Recently new high spin data have been reported for the ^{147}Ce nucleus in Ref. [25]. The $|D_0|$ moments calculated from the B(E1)/B(E2) values given in this reference are 0.18(1) and 0.21(2) efm for the $31/2^-$, 2703.1 keV and $35/2^-$, 3264.0 keV levels, respectively. These values are comparable to the average $|D_0|$ values of 0.19(3) and 0.21(2) efm obtained from the B(E1)/B(E2) values in the neighboring ^{146}Ce [26] and ^{148}Ce [27] isotopes, respectively.

It seems that considered opposite parity states in $^{147,149}\text{Nd}$ and in ^{149}Ce may not constitute parity doublets and the main octupole strength is located at higher

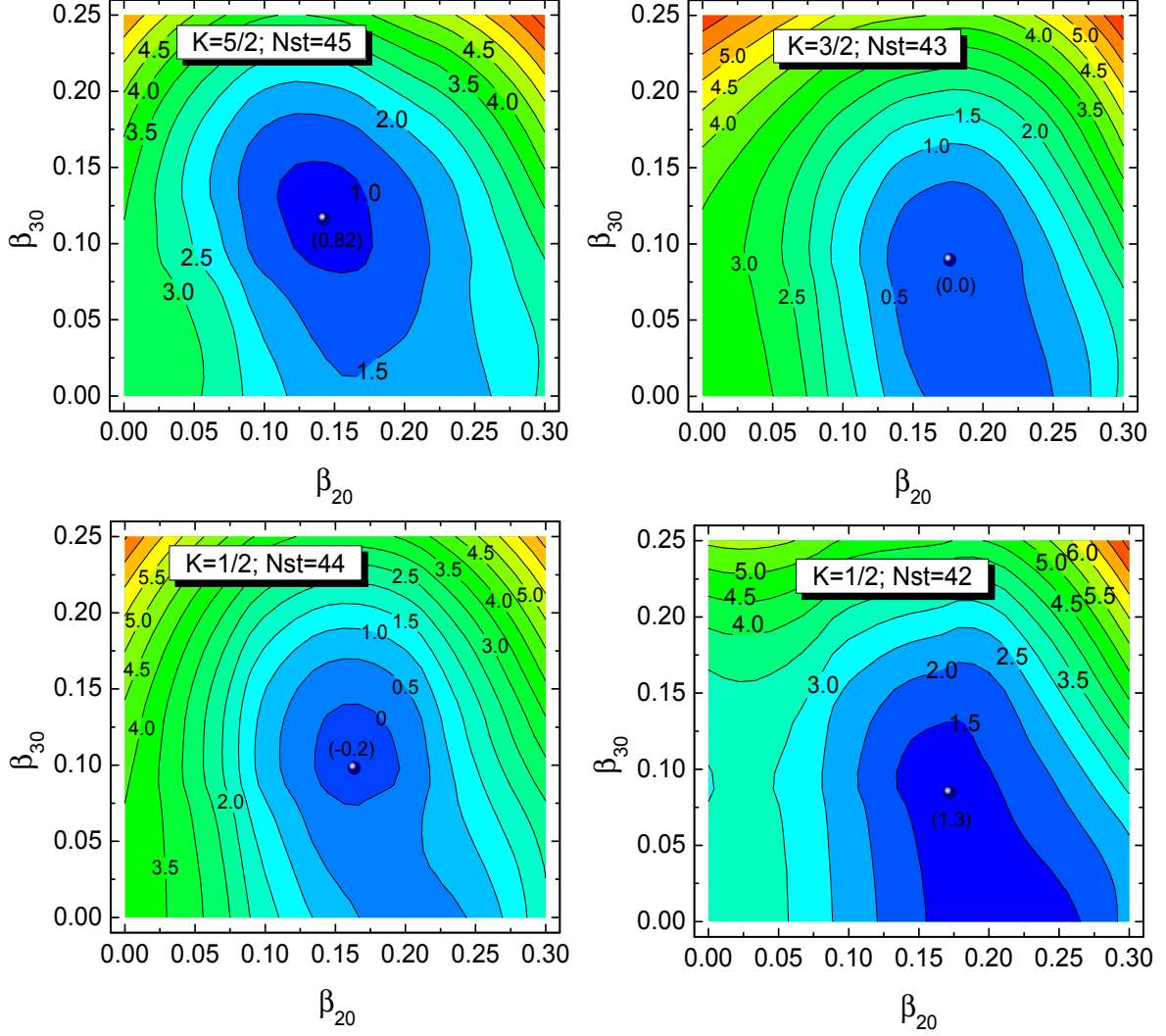


FIG. 8: Potential energy surfaces calculated for the lowest single quasi-particle configurations in ^{147}Nd with $K = 1/2, 3/2$ and $5/2$ and single particle state numbers $Nst = 42, 43, 44$ and 45 . The energy distance between the contour lines is equal to 0.5 MeV.

TABLE III: Experimental and theoretical $|D_0|$ values in Nd isotopes (in efm).

N Isotope	84 ^{144}Nd	85 ^{145}Nd	86 ^{146}Nd	87 ^{147}Nd	88 ^{148}Nd	89 ^{149}Nd	90 ^{150}Nd
Experiment	0.12(1) ^a		0.16(4) ^b	$\geq 0.02^c$	0.21(4) ^b	0.06(2) ^d	0.26(5) ^b
Theory ^c		0.15	0.17	0.26	0.30	0.36	

^adetermined from level lifetime data given in the www.nndc.bnl.gov data base.

^bfrom Ref. [2].

^cthis work.

^dfrom Ref. [3].

excitation energies. It is possible that the presence of odd neutron blocks octupole correlations at low excitation energies in the odd N isotopes. More experimental information on the parity doublets and dipole moments in ^{147}Nd and in other odd N isotopes in lanthanides is needed to understand the $|D_0|$ moments behavior in nuclei from this region.

C. Potential energy surfaces

Energy surfaces over (β_{20}, β_{30}) plane were calculated for the lowest single-particle configurations in ^{147}Nd by using the macroscopic-microscopic method. Macroscopic energy was calculated using the Yukawa plus exponential model [28] with parameters specified in [29]. A deformed Woods-Saxon potential [30] with the universal set of parameters [31] was used to calculate the microscopic energy.

We used a β parametrization, $\beta = (\beta_{20}, \beta_{30}, \beta_{40}, \beta_{50}, \beta_{60}, \beta_{70}, \beta_{80})$, in which the shape of a nucleus is described by the formula:

$$R(\theta) = R_0 c(\{\beta\}) \left\{ 1 + \sum_{\lambda=2}^8 \beta_{\lambda 0} Y_{\lambda 0}(\theta) \right\}. \quad (2)$$

where $R(\theta)$ is the nuclear radius and $c(\{\beta\})$ is the volume-fixing factor.

Considered single particle configurations were chosen by blocking the odd neutron on a desired single particle state with a given K . Energies were calculated on a grid of 1361367 points defined by deformation values:

$$\begin{aligned} \beta_{20} &= 0.00 \text{ (0.05) } 0.30; \\ \beta_{30} &= 0.00 \text{ (0.05) } 0.30; \\ \beta_{40} &= -0.20 \text{ (0.05) } 0.20; \\ \beta_{50} &= -0.20 \text{ (0.05) } 0.20; \\ \beta_{60} &= -0.15 \text{ (0.05) } 0.15; \\ \beta_{70} &= -0.15 \text{ (0.05) } 0.15; \\ \beta_{80} &= -0.15 \text{ (0.05) } 0.15; \end{aligned} \quad (3)$$

where the step in each deformation is given in parenthesis. For each pair (β_{20}, β_{30}) energy was then minimized with respect to $\beta_{40} - \beta_{80}$. Energy surfaces obtained for four single-particle configurations in ^{147}Nd are presented in Fig. 8. They show equilibrium deformations: β_{20} of 0.13 - 0.18 and $\beta_{30} \approx 0.10$. Two configurations, $K = 1/2$ and $3/2$ (energy levels no. 42 and 43) with shallow octupole minima may be called octupole-soft. Slightly more pronounced, ≈ 0.5 MeV deep, octupole minima were obtained for configurations with $K = 1/2$ and $5/2$ (levels no 44 and 45; the Fermi level in ^{147}Nd lies in-between levels no 43 and 44).

Energy calculations for two even-A neighbors of ^{147}Nd show octupole minima for both ^{146}Nd and ^{148}Nd ground states. Thus, our calculations suggest that ^{147}Nd lies inside the lanthanide octupole collective region.

D. Theoretical electric dipole moments

Reduced probabilities of electromagnetic (EM) transitions between the rotational band built on the one-phonon state and the g.s. band can be calculated assuming the fixed structure of both the phonon and the collective rotor [32]. For an operator \mathcal{M} of the multipolarity λ one has in odd-A nucleus

$$B(\lambda; K_1, I_1 \rightarrow K_2, I_2) = 2 \langle I_1 K_1 \lambda K_2 - K_1 | I_2 K_2 \rangle^2 \quad (4) \\ | \langle K_2 | \mathcal{M}(\lambda, K_2 - K_1) | K_1 \rangle |^2$$

with $\mathcal{M}(\lambda, \nu)$ the intrinsic spherical component. For dipole transitions between pear-shaped parity-doublet bands $\mathcal{M}(E1, 0) = [3/(4\pi)]^{1/2} \hat{D}_z$, where the dipole moment $\hat{\mathbf{D}} = e(N \sum_p \mathbf{r}_p - Z \sum_n \mathbf{r}_n)/A$.

In the strong coupling limit with two octupole minima at $\pm \beta_{30}^{eq}$, the transition matrix element D^t is calculated as the intrinsic dipole moment at this deformation of equilibrium. In this case, $\beta_{30}^{eq} = \beta_{30}^{\pi-}$, the expectation value of β_{30} in the first excited state of negative parity, nearly degenerate with the g.s.

For shallow minima, closer to oscillation scenario, the degeneracy between parity-doublet bands is shifted. The transition matrix element in the intrinsic frame between the g.s. and the lowest excited state of negative parity $|\pi-\rangle$ may be approximated by a diagonal matrix element of the transition operator in the mean-field state with the deformations β_{30}^{tr} fixed as the most probable by the transition density. For a harmonic lowest-lying phonon one has the relation $\beta_{30}^{tr} = 0.63 \beta_{30}^{\pi-}$ which follows from the one-dimensional harmonic oscillator.

We calculated expectation values of the electric dipole moment in the intrinsic states as a sum of the macroscopic and shell-correction parts, see e.g. [1, 33]. The macroscopic part, derived within the Droplet Model in [34], was calculated as in [35], i.e. without assuming small deformations $\beta_{\lambda 0}$. It turns out (Table III) that intrinsic dipole moments at equilibrium deformations for two configurations: $K = 1/2$ and $3/2$ (levels no 43 and 44) interpolate the values for $^{146,148}\text{Nd}$. Both macroscopic and shell correction contributions have the same sign, so no reduction of D_0 due to their cancellation is possible. Thus, the dipole moments inferred from experiment do not fit the picture of parity doublet bands.

V. SUMMARY

The advanced time-delayed $\beta\gamma\gamma(t)$ method has been used to measure half-lives of 8 excited states in ^{147}Nd . Reduced transition probabilities were obtained for 30 transitions. Twenty-four new γ -lines and 3 new levels have been introduced into the decay scheme of ^{147}Nd based on the results of the β -gated $\gamma\gamma$ coincidence measurement.

The potential energy surfaces on the (β_2, β_3) plane and theoretical $|D_0|$ values suggest the presence of octupole

deformation in ^{147}Nd at low excitation energies for two configurations with $K=1/2$ and $K=5/2$. This suggestion is supported by high experimental $|D_0|$ values in two even-even neighbors of ^{147}Nd . For the $K=1/2$ configuration we were able to determine only lower limit of the dipole moment, $|D_0| \geq 0.02 \text{ e.f.m.}$ However non-observation of the $K=5/2$ parity doublet band may suggest that in ^{147}Nd the $|D_0|$ values are as low as observed in other odd N isotopes at low excitation energies. Probably strong octupole correlations should be searched at higher excitation energies in the odd N isotopes from the lanthanides octupole region.

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